Towards Intelligent Control via Genetic Programming

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Background and Aim of the work

Aim:
- to investigate the use of Genetic Programming for the design of (intelligent) control systems

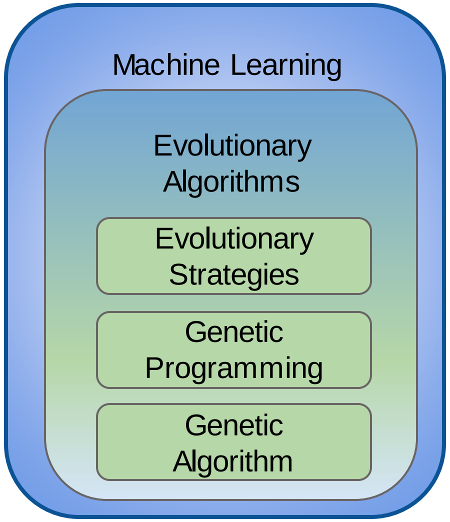
Rationale:
- Challenges presented by Hypersonic Vehicles, Space Access Vehicles and Space Exploration require a new approach to control design to improve performances and robustness beyond the limits of current standard approaches.

An Intelligent Control (IC) application using GP on a modified version of the Goddard Rocket test case is proposed.

[1] B. Xu, Z. Shi. An overview on flight dynamics and control approaches for hypersonic vehicles. Science China Information Sciences. 2015
[2] Y. Xie, H. Huang, Y. Hu, G. Zhang. Applications of advanced control methods in spacecrafts: progress, challenges, and future prospects. Frontiers of Information Technology & Electronic Engineering. 2016.
[3] D. Izzo, M. Martens, B. Pan. A survey on artificial intelligence trends in spacecrafts guidance dynamics and control. Astrodynamics. 2019

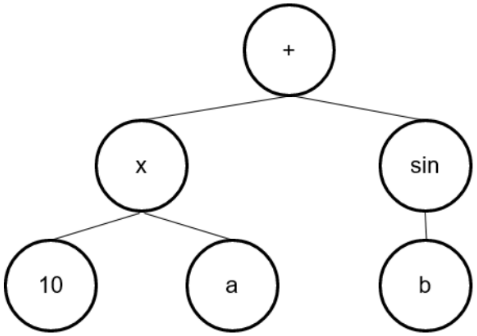
Genetic Programming

- Originally introduced by Koza* .
- Pertain to the class of Evolutionary Algorithms.
- Allow the creation of computer programs following the laws of natural evolution.



GP applied to controller design:

- Both topology and parameters of the controller can be defined and optimized by GP**.
- When nonlinearities are introduced in the system, the definition of a new kind of controller is necessary.
- Unlike other ML techniques, GP produces mathematical equations which could be analysed by the user with classical control techniques.



$(10 \times a) + \sin(b)$

* J.R. Koza. Genetic Programming: On the Programming of Computers by Means of Natural Selection. 1992
** J.R.Koza, M. A. Keane, J. Yu, F. H. Bennet III, W. Mydlowec. Automatic Creation of Human-Competitive Programs and Controllers by Means of Genetic Programming. Genetic Programming and Evolvable Machines. 2000

What is intelligent control?

"An intelligent control system is designed so that it can autonomously achieve a high level goal, while its components, control goals, plant models and control laws are not completely defined, either because they were not known at the design time or because they changed unexpectedly."*

Chosen approach to Intelligent control through GP:

- Thrust (control parameter) composed by the reference (obtained from open-loop optimal control) and a function of the relative errors created through GP.

- f_{GP} is created when a change in the environment or in the system occurs.

$$T = T_{ref} + f_{GP}(e_1, \ldots, e_n)$$

Main issues:

- GP is computationally expensive.

- GP evaluation initial conditions must be defined a priori --> **define evaluation time a priori!**

* P. Antsaklis. Defining Intelligent Control. Report of the Task Force on Intelligent Control, IEEE Control System Magazine, June 1994.
[7] G. N. Saridis. Toward the realization of Intelligent Controls. Proceedings of the IEEE, Vol. 67, No. 8. 1979
[8] C. Wilson, F. Marchetti, M. Di Carlo, A. Riccardi, E. Minisci. Intelligent Control: A Taxonomy. 8th International Conference on Systems and Control (ICSC). 2019.

Test Case: Goddard Rocket 2 Controls

The chosen test case is a modified version of the Goddard Rocket as a first step for a future application on a more complex model of a space access vehicle. The optimal trajectory was obtained with a Pseudospectral Collocation method*.

$$\begin{cases} \dot{r} = v_r \\ \dot{\theta} = \frac{v_t}{r} \\ \dot{v}_r = \frac{T_r}{m} - \frac{D_r}{m} - g + \frac{v_t^2}{r} \\ \dot{v}_t = \frac{T_t}{m} - \frac{D_t}{m} + \frac{v_t v_r}{r} \\ \dot{m} = -\frac{\sqrt{T_r^2 + T_t^2}}{g_0 I_{sp}} \end{cases}$$

$$D_r = \frac{1}{2}\rho v_r \sqrt{v_r^2 + v_t^2} C_d S$$

$$D_t = \frac{1}{2}\rho v_t \sqrt{v_r^2 + v_t^2} C_d S$$

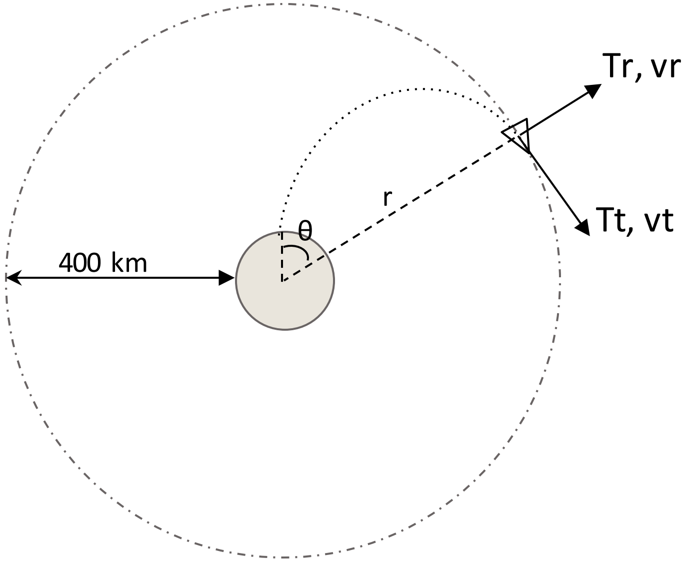
$$\rho = \rho_0 e^{-\beta r}$$

Where:

- $Cd = 0.6$
- $S = 4.0\ m^2$
- $I_{sp} = 300\ s$
- $m_0 = 100000\ kg$
- $m_p = 0.99 * m_p$

Mission goals:

- reach an altitude of 400 km
- using less propellant as possible

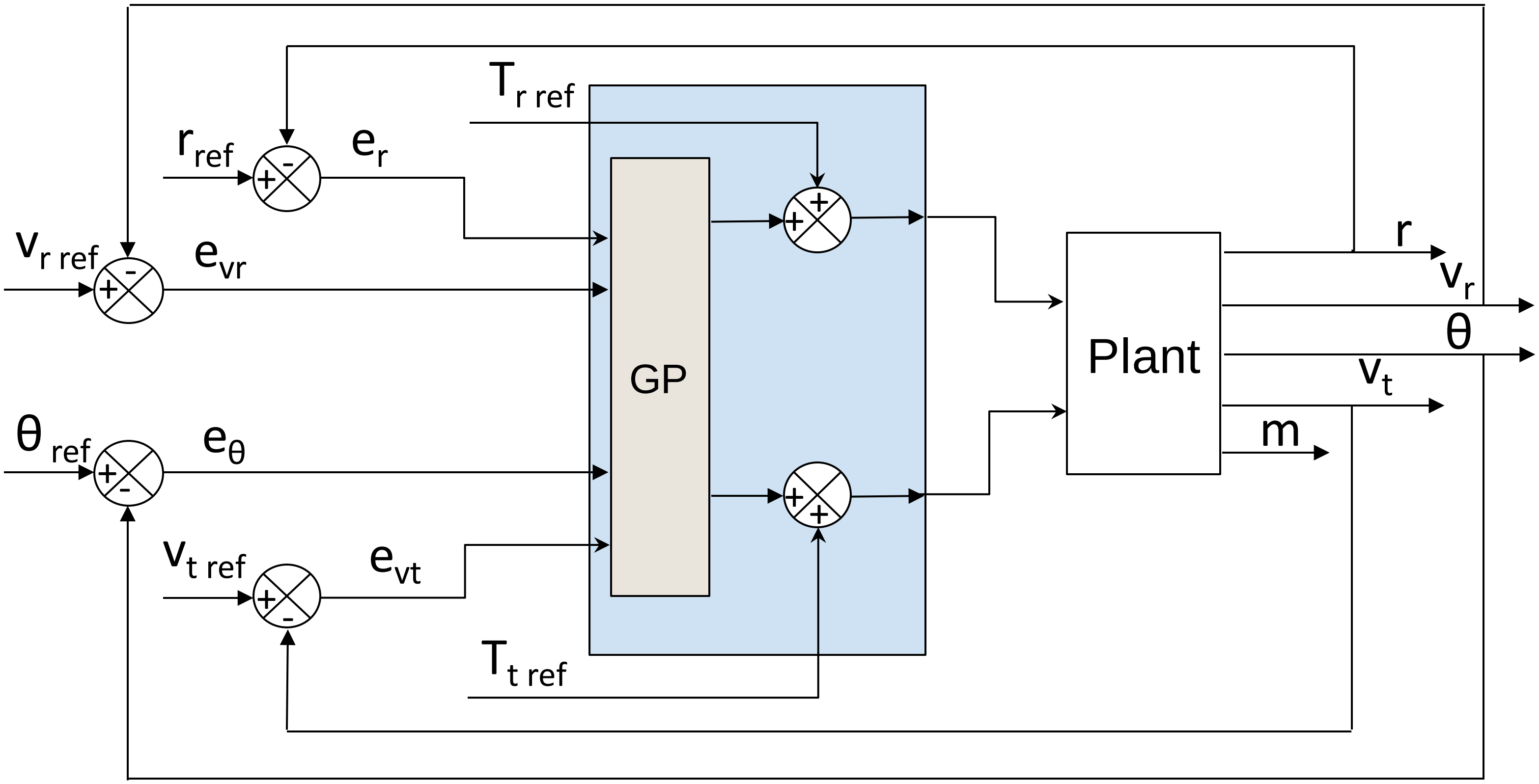


* Istellartech. OpenGoddard open source library. https://github.com/istellartech/OpenGoddard. 2017

Control scheme

$$T_r = T_{r_{ref}} + f_{GP_r}(e_r, e_{v_r})$$

$$T_t = T_{t_{ref}} + f_{GP_t}(e_\theta, e_{v_t})$$



3 scenarios are presented:

1. Variation of Cd at a random time and by a random magnitude.

2. Wind gust acting in a random altitude range with a constant random intensity in horizontal direction.

$$v_r = v_r - v_{wind} \sin\theta$$
$$v_t = v_t - v_{wind} \cos\theta$$

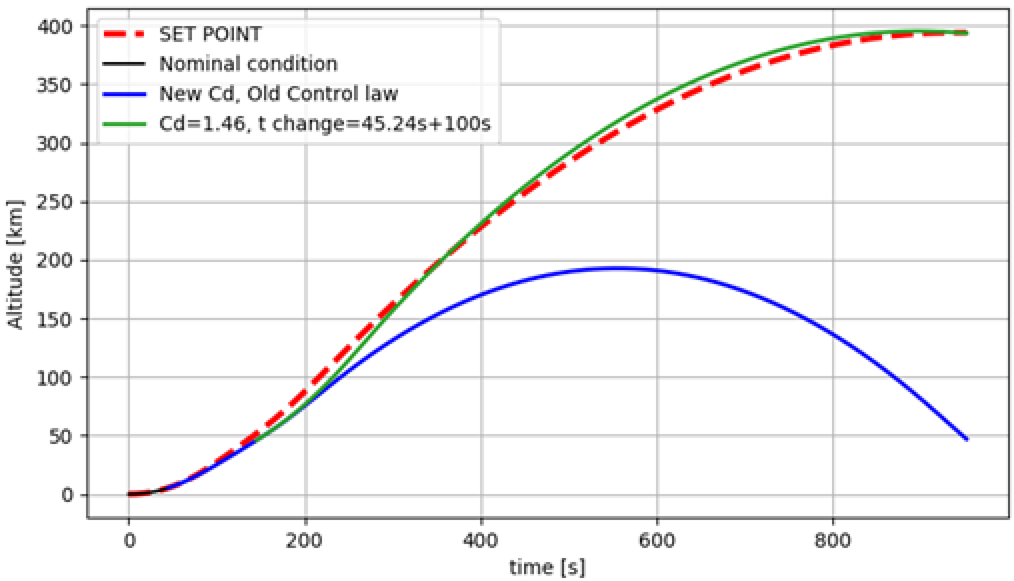
3. Real density model unknown at design time. Optimal trajectory obtained with simplified model and the real model is estimated during flight along with the controller law.

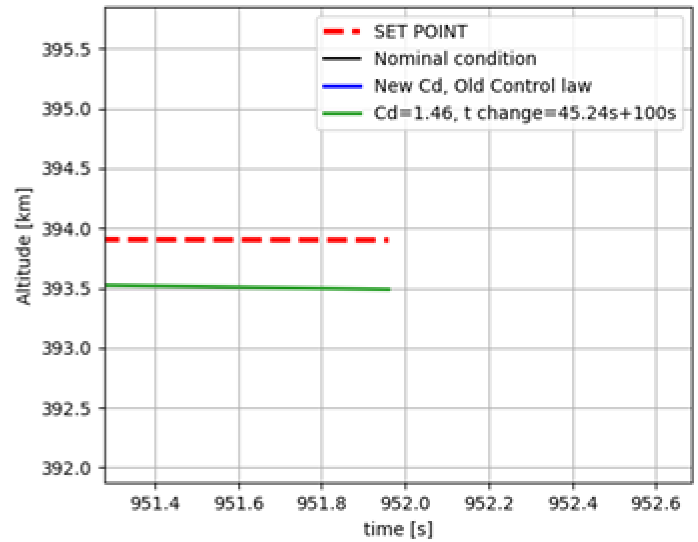
$$\rho = \rho_0 e^{-\beta r} \Longrightarrow \rho = \rho_{ISA}(r)$$

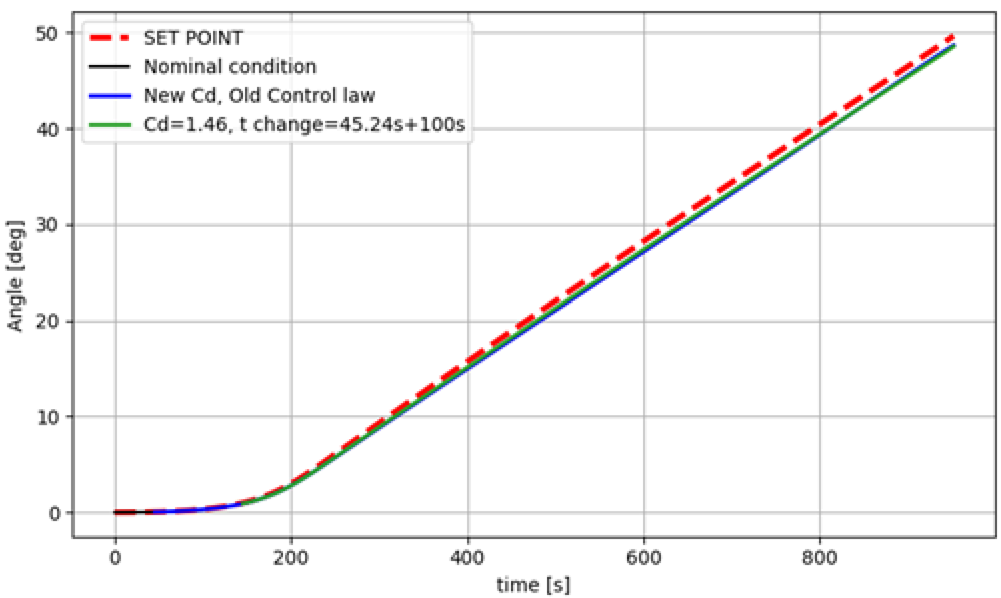
All simulations were run on a PC with 8GB of RAM and an Intel®Core™ i7-6700 CPU @3.40 GHz x 8 processors.
The scripts were coded in Python relying on the open source library DEAP*.

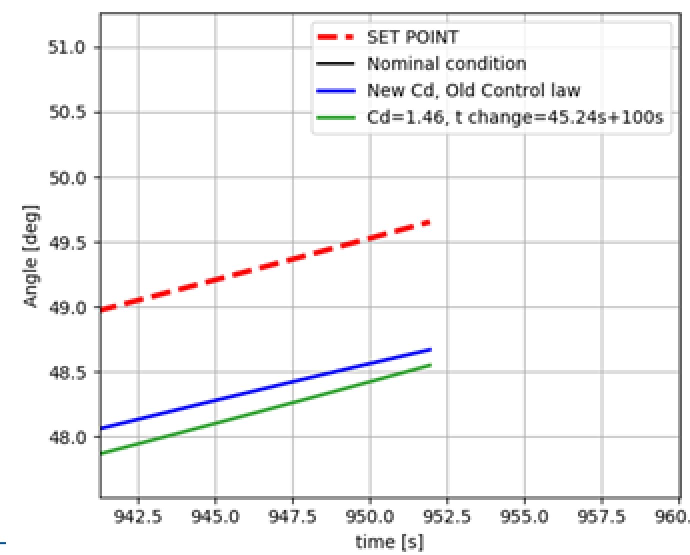
* F.-A. Fortin and F.-M. De Rainville and M.-A. Gardner and M. Parizeau and C. Gagné. DEAP: Evolutionary Algorithms Made Easy. Journal of Machine Learning Research. 2012

Results: Scenario 1 - Cd variation

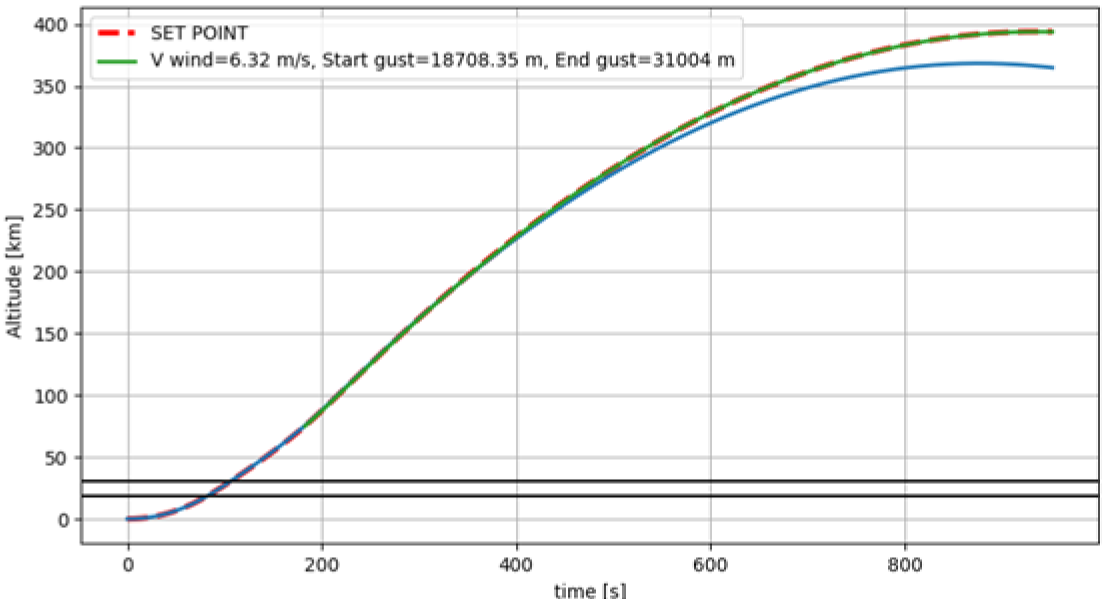


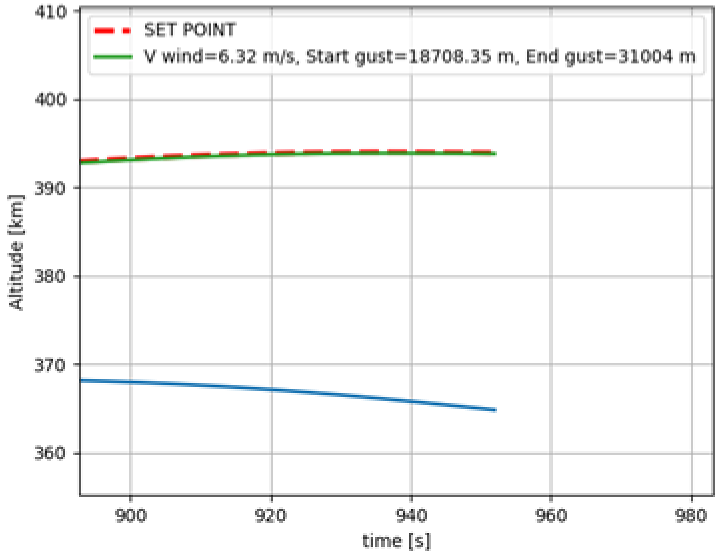


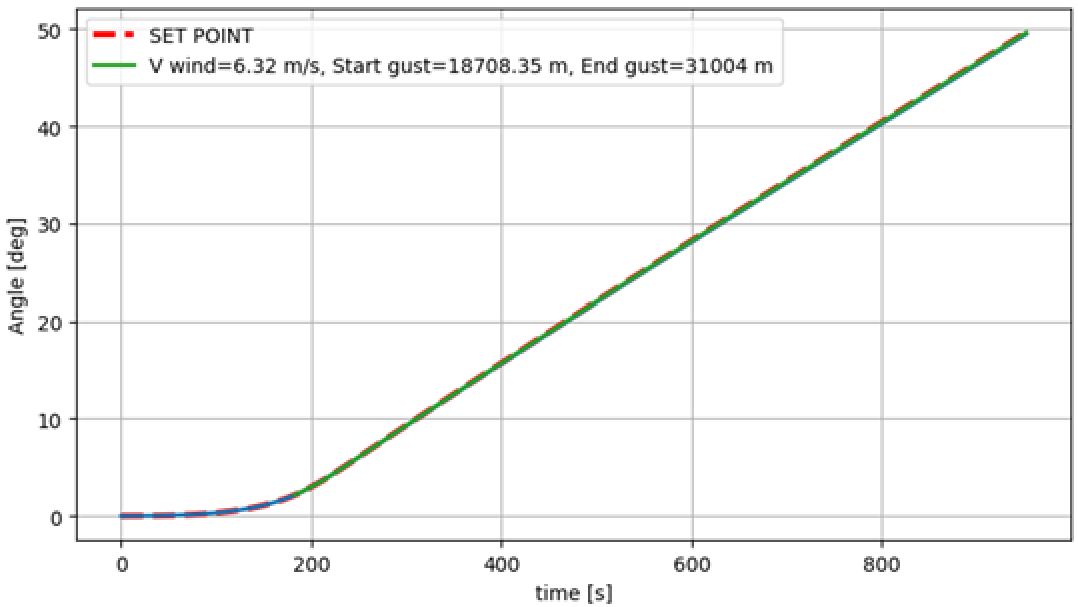


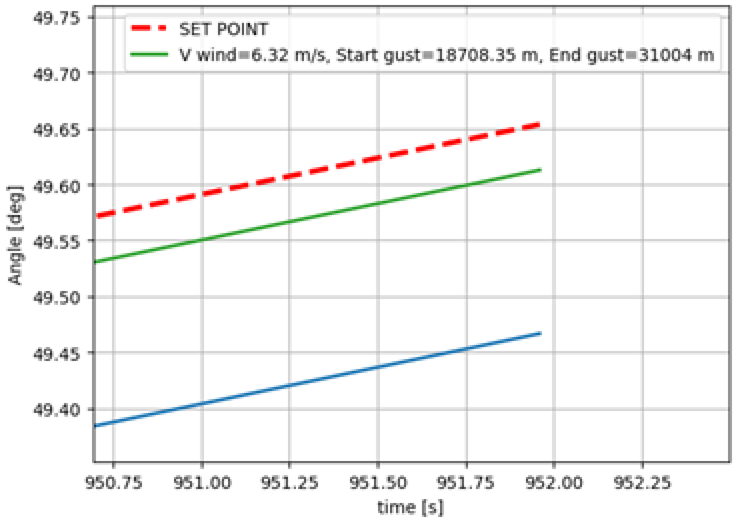


Results: Scenario 2 - Wind Gusts

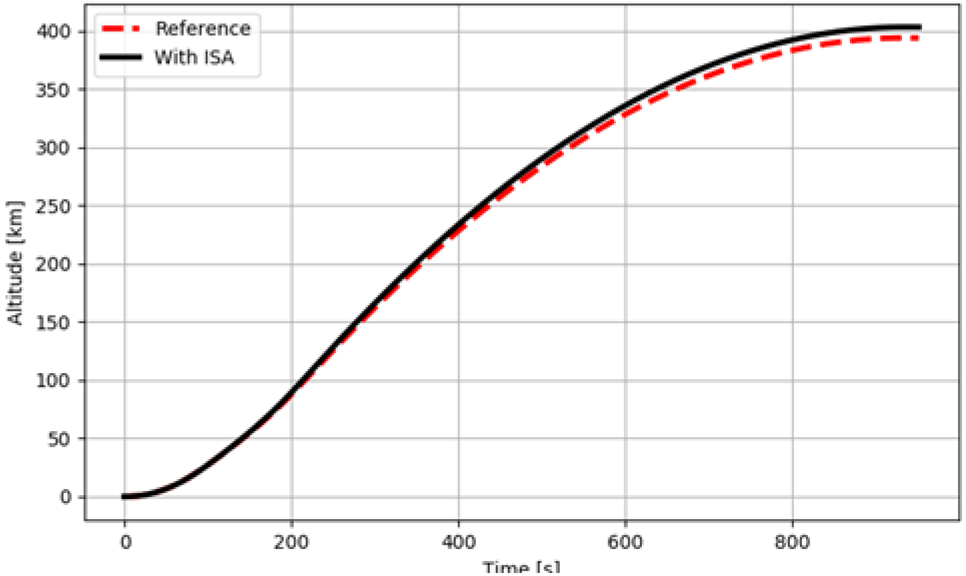


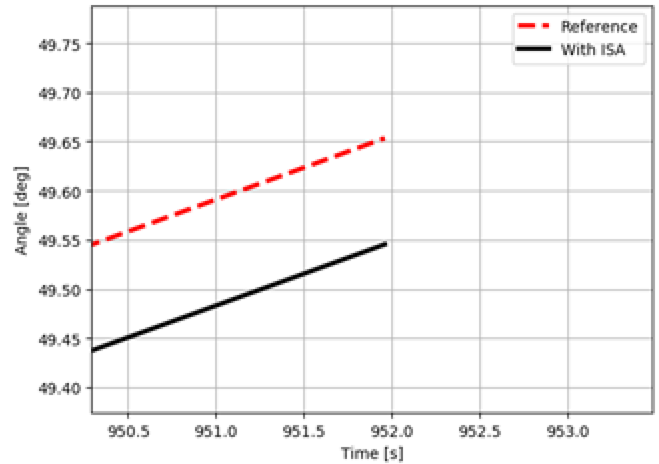


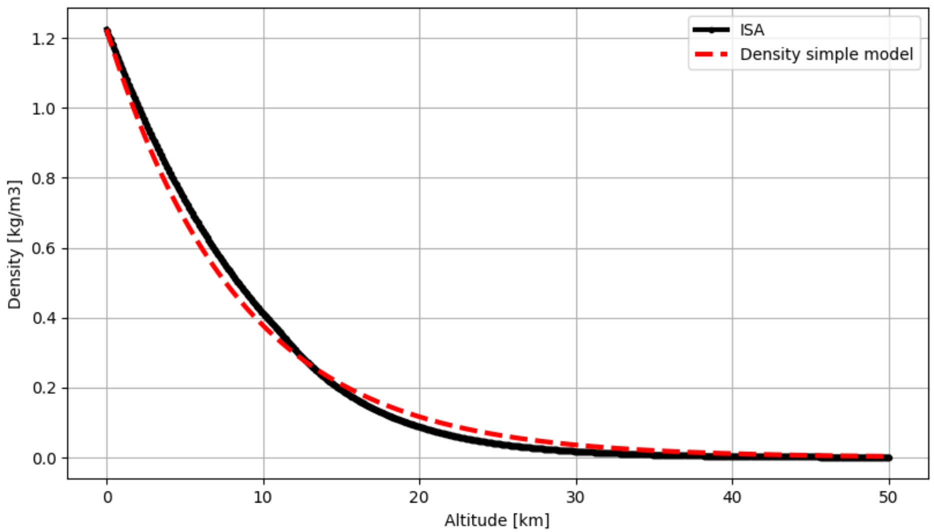


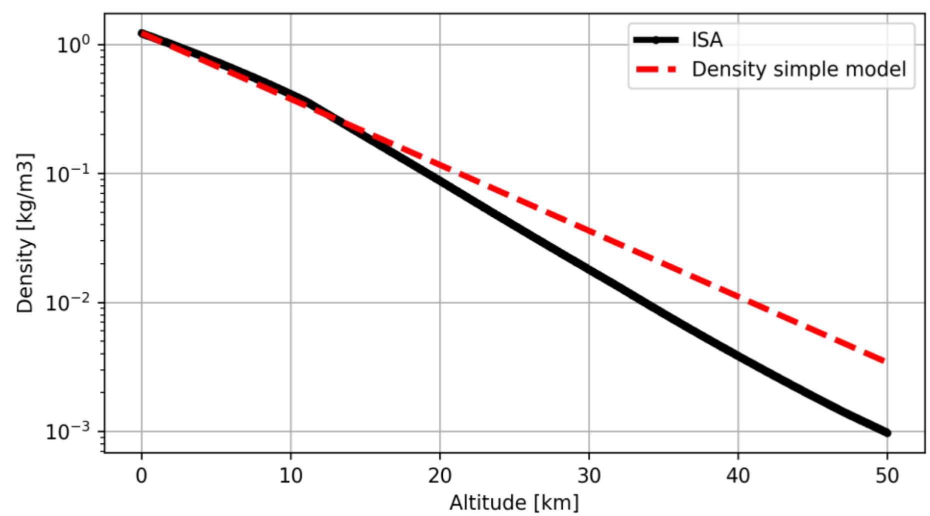


Results: Scenario 3 - Unknown density model









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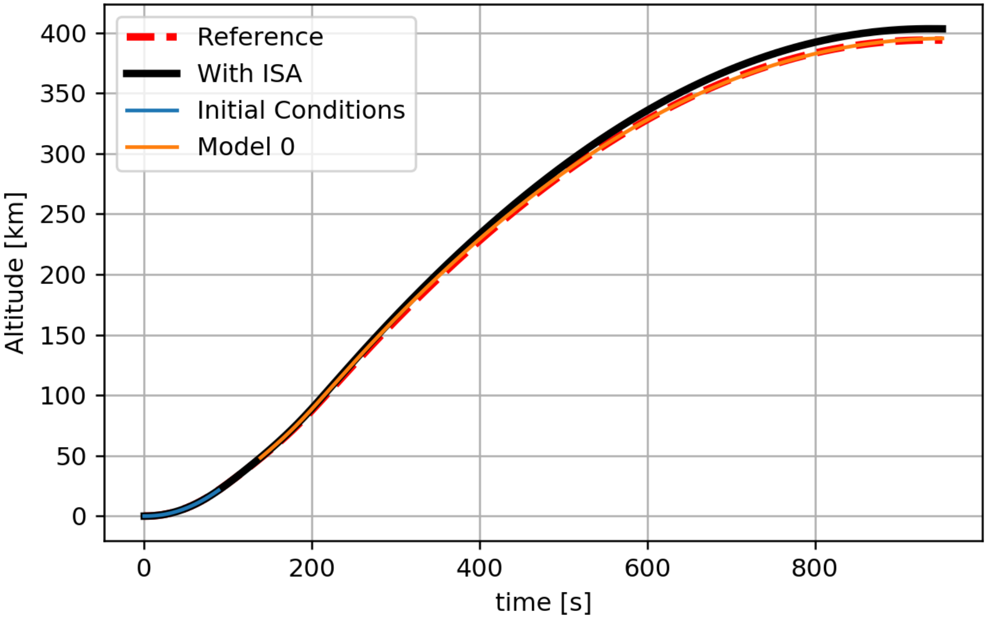

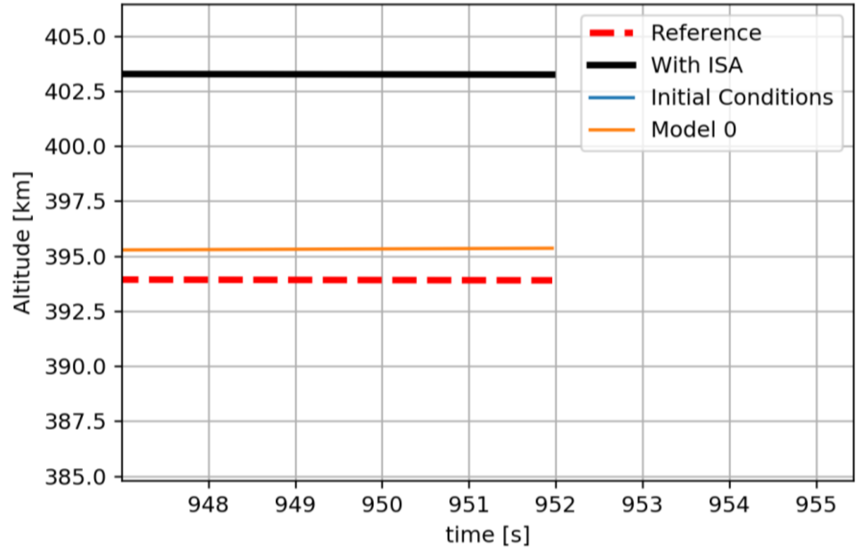

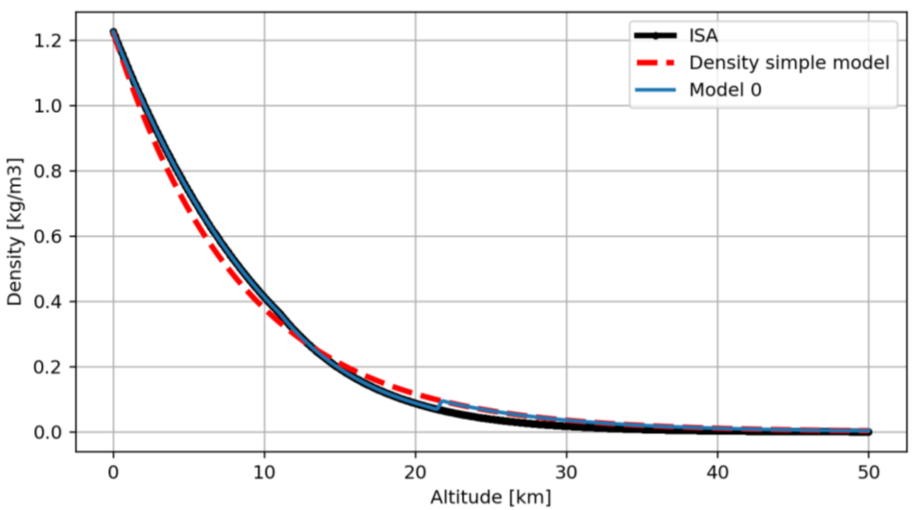

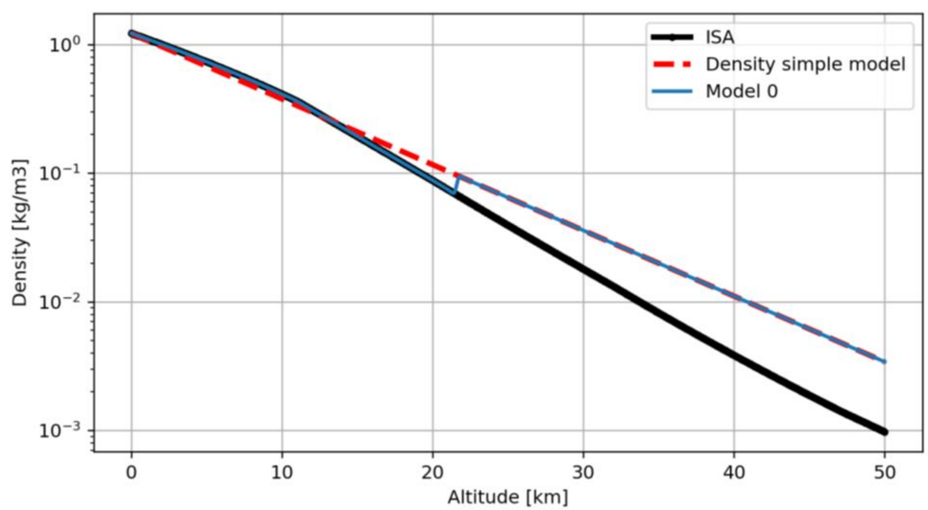

Results: Statistics

	Cd Variation		Wind Gust		Density Model	
	No learning	Learning	No learning	Learning	No learning	Learning
GP Evaluations	100	100	100	100	270	199
Fixed evaluation time interval	100 s	100 s	100 s	100 s	50 s	50 s
Min evaluation time	3.63 s	8.11 s	8.76s	9.98 s	2.94 s	7.25 s
Max evaluation time	06h08m50s	01h27m37s	38m41s	55m59s	23m09s	18m41s
Time Constraint Success Rate	66%	76%	44%	62%	40%	49%
Range Constraint Success Rate	61%	64%	100%	100%	71%	82%
Total Success Rate	51%	60%	44%	62%	7%	46%

Conclusions and Future Work

Conclusions:

- GP can be a powerful tool to design a control law, with very good generalization capabilities.
- The biggest issues for a practical use of GP for IC is its computational cost.

Future work:

- Implement more sophisticated methods to integrate models with "measured" data.
- Couple GP with an ANN, so to avoid the re-evaluation of the entire control law and perform the optimization of its components when needed.

Summary:

- Introduction
- Genetic Programming
- Intelligent Control
- Test Case
    - Results
- Conclusions and future work

References

[1] B. Xu, Z. Shi. An overview on flight dynamics and control approaches for hypersonic vehicles. Science China Information Sciences. 2015

[2] Y. Xie, H. Huang, Y. Hu, G. Zhang. Applications of advanced control methods in spacecrafts: progress, challenges, and future prospects. Frontiers of Information Technology & Electronic Engineering. 2016.

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[9] Istellartech. OpenGoddard open source library. https://github.com/istellartech/OpenGoddard. 2017.

[10] F.-A. Fortin and F.-M. De Rainville and M.-A. Gardner and M. Parizeau and C. Gagné. DEAP: Evolutionary Algorithms Made Easy. Journal of Machine Learning Research. 2012.

THANKS

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